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Scientific paper

Investigation on Properties of ECC Incorporating Crumb Rubber of Different Sizes

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Abstract

In the past decades, incorporating crumb rubber into concrete has attracted attention in the field of building materials due to the properties improvement it brought. In this study, crumb rubber of two particle sizes (40CR and 80CR, which have a sieve size of 400 μm and 220 μm , respectively) is incorporated into engineering cementitious composite (ECC) material to replace silica sand. Furthermore, three different replacement percentages (0, 15%, 25% by volume) for each crumb rubber size are conducted in this study. The influence of crumb rubber on the ECC is revealed via density, compressive strength, flexural performance, drying shrinkage, restrained shrinkage and environment footprint. The experimental results show that the incorporation of crumb rubber into ECC increases bending deformation capacity, decrease density and compressive strength. While the free drying shrinkage of ECC increases with the addition of crumb rubber, lesser crack number, crack width and cracking tendency were found in the restrained ring test when compared to ECC without crumb rubber. In terms of crumb rubber size, ECC with smaller crumb rubber appear to have lower density and higher bending defatation capacity and shrinkage than those with larger crumb rubber. In addition, incorporating crumb rubber into ECC reduces CO₂ emission, thus improve the greenness of ECC to a certain degree.

1. Introduction

With the development of the rubber and automobile industries, the growing amount of waste rubber, rubber products and angle scrap produced from scrap tires has raised ever-increasing environmental concern. Meanwhile, the disposal of waste tire rubber has been a very thorny problem to governments in the world. Generally, the cheapest and easiest way to dispose the used tires is by burning them. However, the pollution caused by enormous amount of smoke during burning makes this method so unacceptable that it is prohibited by law in many countries (Siddique and Naik 2004; Sukontasukkul and Chaikaew 2006). Besides that, the discarded tires are also disposed by burying with other industrial waste in landfills or stockpiling in huge dumps. However, the stockpiles not only hazard environment potentially but also provide breeding grounds for rats, mice, vermin and mosquitoes (Naik and Singh 1991; Singh 1993). Furthermore, landfills has become increasingly unaccepted due to limited availability of sites for waste disposal, and some countries such as France has issued new law to forbid any new landfill. Huge volume of accumulated used tires has been the main waste management problem. Therefore, recycling and utilization of the waste tires seems to be necessary.

In the past two decades, significant research work has been carried out to incorporate rubber powder produced by grinding used tires into cement-based materials like concrete (Topcu 1995; Garrick 2005; Sukontasukkul and Chaikaew 2006; Hernández-Olivares *et al.* 2007; Khatib and Bayomy1999; Donaldson 2010). After the addition of tire rubber powder, the overall research results indicated a remarkable reduction in strength and stiffness properties of the concrete. Despite the significant decrease in the strength properties, the composites still satisfy the basic requirements of construction materials (Ho *et al.* 2008). Furthermore, the addition of crumb rubber can also decrease density of concrete while increase drying shrinkage (Sukontasukkul and Tiamlom 2012; Ho *et al.* 2012). Nevertheless, the cracking resistance was improved due to the enhanced strain capacity (Huang *et al.* 2013). In addition, replacement of natural aggregate with rubber particles provided significant increase in toughness and ductility as well as better damping capacity of the concretes (Nehdi and Khan 2001; Hernandez-Olivarez *et al.* 2002; Gesog and Guneyisi 2007; Reda Taha *et al.* 2008). Considering the above benefits waste rubber powder brought into concrete, it is worthwhile to conduct some research on the influence of crumb rubber on the properties of engineered cementitious composite (ECC).

ECC is a kind of high-performance fiber-reinforced cementitious composites (HPFRCC) with a unique property of high ductility with medium fiber content, which was designed based on micromechanics theory by Victor Li at 1990s (Li 1993). Tensile strain capacity of ECC materials ranges from 3 to 5%, which have been demonstrated using polyethylene fibers and polyvinyl alcohol (PVA) fibers with fiber volume percentage less

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Table 1 Properties of PVA fibers.

Fiber type	Diameter (μm)	Length (mm)	Tensile strength (MPa)	Modulus (GPa)	Density (g/cm^3)
Kuraray PVA fiber	39	8	1600	42	1.3
Chinese PVA fiber	30	12	1200	22	1.3

than 2% (Li 1998; 2002). Unlike the continuous widening of one localized crack in normal concrete, multiple tiny cracks (typically below $100\ \mu\text{m}$) developed sequentially in ECC before final fracture which contributes its large strain capacity. With such tiny cracks in ECC, the water permeability coefficient and chloride diffusion property were found to be nearly the same as that of sound concrete (Sahmaran *et al.* 2007; Lepech and Li 2009). From this perspective, the cracks formation (which is inevitable to concrete materials) in ECC is expected to have little impact on transport properties and durability. The associated high fracture toughness, high ductility and tight crack width control capacity make ECCs an ideal material to improve durability of the civil infrastructures, thus prolong its service life.

Although the utilization of waste rubber in concrete has attracted attentions in the field of building materials in the past decades, the research on ECC incorporating crumb rubber is very limited. One most relevant paper was published by Huang *et al.* recently (2013). They carried out some investigations based on recycled tire rubber, in their study; they found that the addition of crumb rubber can increase ECC's tensile strain capacity and enhanced its cracking resistance. Nevertheless, they did not investigate the effect of crumb rubber size on ECC's properties, flexural properties, as well as restrained shrinkage and impact on environment.

ECC with crumb rubber replacement of silica sand (three replacement percentages are referred for both crumb rubber size in this study) is proposed. This paper focuses on the density, flexural performance, compressive strength, drying shrinkage and restrained shrinkage of ECC with the incorporation of crumb rubber. Finally, the environment footprint is also given. In the following sections, the experimental program is introduced firstly. The experimental program is useful in understanding the process of experiment. Then the experiment results and discussion are reported.

Fig. 1 The look of Crumb rubber particles.

2. Experimental programs

2.1 Materials and mix proportions

In this paper, ingredients include ordinary Portland cement, fly ash (FA), silica sand, crumb rubber, water, Kuraray polyvinyl alcohol (PVA) fiber and polycarboxylate-based high water reducer (HRWR) were used in the production of ECC mixtures. The geometrical and mechanical properties of PVA fibers are described in Table 1. The parameters of Chinese PVA fiber listed in Table 1 will be used to discuss the influence of crumb rubber on interface parameters in section 3.3. The look of crumb rubber particle is shown in Fig. 1. Figure 2 presents the grade curves of silica sand and crumb rubber, which shows that the particle size distribution of 80CR is very close to that of silica sand. The density of two kinds of crumb rubber and silica sand is $1.19\ \text{g}/\text{cm}^3$ for 80CR, $1.27\ \text{g}/\text{cm}^3$ for 40CR and $2.60\ \text{g}/\text{cm}^3$, respectively.

To investigate the influence of incorporation of crumb rubber on the performance of ECC material, five ECC mixtures with the same water-binder ratio of 0.25 and the same fly ash-cement ratio of 2.2 were adopted in this study. The mix proportion of all mixtures is listed in Table 2. The 80CR is used in M2 and M3, while 40CR is used in M4 and M5. The variable parameter in ECC mixture is the crumb rubber replacement ratio (15%, 25% by volume of silica sand). The standard mixture without crumb rubber is also studied as the control mixture.

Five ECC mixtures were all used for four-point bending test, compressive strength and free drying shrinkage. All ECC mixtures were mixed in the standard mixing process. All solid ingredients including cement, fly ash, silica sand, and crumb rubber were mixed dry for 3 minutes before adding water. Water and HRWR were then added into the dry mixture for another 3 minutes. Then PVA fiber were slowly added into the mortar and mixed for 5 minutes until fibers were dispersed well. The

Fig. 2 Grade curve of crumb rubber and silica sand.

Table 2 Mixture proportion of ECC mixture (g/L).

Crumb rubber	Mix ID	Cement	Fly ash	Sand	Crumb rubber	Water	HRWR	PVA
	M1	395	868	459	0	312	6	26
80CR	M2	395	868	390	31	312	6	26
80CR	M3	395	868	344	51	312	6	26
40CR	M4	395	868	390	33	312	6	26
40CR	M5	395	868	344	55	312	6	26

fresh ECC was then cast into steel formwork and subsequently demolded after 1 day curing. All the specimens except that for drying shrinkage and restrained shrinkage ring test were then cured at the temperature of 20°C and relative humidity of 95% for 60 days.

2.2 Specimens preparation and testing

For each mixture, three specimens were prepared for compressive test and bending test. The dimensions of compressive and bending specimen were 70.7×70.7×70.7 mm and 400×70×16 mm, respectively. The compressive strength and bending properties were obtained by taking average the results of three specimens.

Four-point bending test was used to evaluate the bending deformation capacity of ECC. The test was conducted under quasi-static loading condition with deformation control of 0.0125 mm/s. The full span length was 300 mm with middle span of 100mm. During the test, the loading stress and loading point displacement were recorded by computerized data recording system. The load-displacement behavior, first cracking strength, flexural strength and toughness index can be obtained from this test. The crack width and the crack number were measured after unloading using portable microscope with minimum scale of 10 μm. For each mixture, the average crack width is obtained from the crack number of 30-50 for each specimen.

To study the variation of matrix fracture toughness after incorporating crumb rubber, the fracture toughness of M1, M2, and M3's matrix was measured with samples' dimension of 304.8×38.1×76.2 mm, according to ASTM E399 using a three-point bending test setup (2013). The full span length of bottom support for the beam was 254 mm and the notch depth (at the longitudinal center of the beam) to beam height ratio was 0.4. During the test, the fracture load was recorded and the matrix fracture toughness was calculated using the recording data, in accordance with ASTM E399.

To investigate free drying shrinkage of ECCs, three specimens were prepared for each mixture with dimensions of 285×25×25 mm in accordance with ASTM C157/C157M (2008). After casting, all specimens were covered by plastic bag on surface and cured at 20°C and relative humidity of 95% for 24 h and then demolded. Subsequently, the specimens were stored in air at room temperature of 25±3°C and relative humidity of 50±5%. Change in specimens length is measured weekly until the age of 90 days. Meanwhile, the density of prism specimen was measured every day until the difference was

less than 0.5% between the last two measurements.

Ring test was used to evaluate the cracking behavior of ECC mixtures under restrained shrinkage conditions. The test setup is in accordance with ASTM C-1581 (2009). A 75 mm thick layer of ECC mixture was casted around a rigid steel ring with a height of 150 mm and inner-outer diameters of 330 mm and 405 mm, respectively. After casting, the top surface of fresh ECC was sealed by silica rubber immediately. The ring specimens were cured in the mold for 24 h before removing the outer ring mold, and then exposed in air at temperature of 23±3 °C and relative humidity of 20±3%. To track the development of restrained shrinkage, two strain gages were attached at the mid-height of inner surface of the steel ring which restrains the shrinkage of ECC specimens. A uniform radial pressure will be exerted on the steel ring due to the shrinkage of ECC, which in turn induces tensile hoop stresses and subsequent cracking on the ECC mortar specimens. For data recording convenience, the strain gages were connected to a data acquisition system in a one fourth-bridge configuration which acquires strain data at 30 min intervals. The steel ring strain measurements were taken immediately after casting and ended after 28 days curing. Then, the crack width and crack length were measured using portable microscope and millimeter with accuracy of 10 μm and 1 mm, respectively.

3. Results and discussions

3.1 Density of ECCs

Results on density are given in Table 3. The density of ECC is found to decrease with the increasing percentage of crumb rubber incorporation. Two possible reasons may explain that. Firstly, the specific gravity of crumb rubber is low (about 45% of the silica sand). Secondly, air bubbles may be trapped at the crumb rubber surfaces during mixing process due to nature non-polar property of rubber, consequently, increases the air content (Khatib and Bayomy 1999). The trapped air bubble at crumb rubber surface submerged in water observed using opti-

Table 3 Density of ECC (kg/m³).

Crumb rubber size	Mix ID	Sand replacement (% Vol.) by Crumb rubber	Density
	M1	0	1830
80CR	M2	15	1660
80CR	M3	25	1600
40CR	M4	15	1710
40CR	M5	25	1640

Fig. 3 Trapped air bubble at crumb rubber surface submerged in water (100X).

cal microscope (100X) is shown in **Fig. 3**. The reduction effect of crumb rubber on density is more pronounced when smaller sized crumb rubber is used. At the same replacement percentage, ECC mixed with crumb rubber No. 80 (80CR) exhibits lower density than the one mixed with crumb rubber No. 40 (40CR). After mixing crumb rubber into ECC, the density of ECCs ranges from 1600 kg/m³ to 1710 kg/m³ which can be classified as light weight concrete according to ACI Committee 213 (1987).

Fig. 4 Compressive strength of ECCs.

3.2 Compressive strength

The material compressive strength for different mixtures can be found in **Fig. 4**. As listed in **Fig. 4**, after incorporation of crumb rubber, compressive strength of ECC mixtures decreases about 35% compared with control mixture M1. Nevertheless, there is no clear difference of compressive strength between crumb rubber ECC specimens with different replacement ratios and crumb rubber sizes. The loss of compressive strength of ECC can be attributed to the increment of porosity caused by the addition of crumb rubber (Bignozzi and Sandrolini 2006; Topcu and Bilir 2009), as well as the unavoidable space generated due to the separation of crumb rubber from hydration products under compression, as shown in **Fig. 5**.

3.3 Flexural performance of ECCs

Three specimens were tested for each mixture to reveal the effect of crumb rubber on flexural behavior. As shown in **Fig. 6**, all ECC specimens exhibit very large deflection capacity under the four-point bending test. The representative flexural stress-load point deflection curves for all mixtures are presented in **Fig. 7**. As shown in the flexural stress–deflection curves, the end point of the linear stage is defined as the first flexural cracking strength, while the maximum flexural stress and corresponding deflection with it are defined as the flexural

Fig. 6 Large deformation of ECC under bending test.

Fig. 5 The morphology of rubber particle and cement paste.

strength and flexural deflection capacity, respectively.

Figure 8 presents the influence of crumb rubber incorporated into ECC on the deflection capacity, first flexural cracking and flexural strength of ECC mixtures at 60 days. The deflection capacity of ECC increases with the amount of crumb rubber. The average deflection of all ECC mixtures changes from 12.6 mm to 31.3 mm. The deflection of ECC incorporating crumb rubber is 1.4-2.5 times that of control mixture. The effect of crumb rubber on deflection capacity is more pronounced when smaller sized crumb rubber is used. At the same replacement percentage, ECC mixed with crumb rubber No. 80 (80CR) exhibits larger deflection capacity than the one mixed with crumb rubber No. 40 (40CR). Flexural deflection capacity of ECC material, which can reflect its ductility (Qian 2007), strongly depends on crumb rubber replacement level (as shown in **Fig. 7** and **Fig. 8**).

The increase of ductility with the addition of crumb rubber can be explained from the micro-mechanics design theory of ECC materials. To enable more saturated micro-cracking and robust ductility of ECC, a sufficient margin between crack tip toughness J_{tip} (proportional to K_m^2) and complementary energy J_b' (calculated from fiber bridging stress versus crack opening σ - δ curve) is needed, and more details can be found in references (Marshall and Cox 1988, Li and Leung 1992). A larger strain-hardening index SHI ($=J_b'/J_{tip}$) indicates a better chance for saturated multiple cracking.

In the three-point bending test determining the matrix's toughness, the load versus displacement relationship of the notched beam specimen is shown in **Fig. 9**. It is found that the load increase linearly with the displacement, therefore the maximum load is adopted to be the fracture force to calculate matrix's fracture toughness (K_m), in accordance with ASTM E399 (2013). As shown in **Fig. 9** and **Table 4**, the fracture force decreases with the addition of crumb rubber, indicating diminishing matrix's fracture toughness K_m . As a result, the matrix's crack tip toughness $J_{tip}(=K_m^2/E_m)$ reduces from 17.7 to 9.2 J/m², whereby the elastic modulus E_m is referenced from Zhang *et al.* (2015).

Recently co-author Hui Ma investigated the influence of crumb rubber on the interface properties between Chinese PVA fiber and matrix by conducting single fiber pull-out test which has not been published. The detailed experiment set-up preparation can be found in the reference (Redon *et al.* 2001). The chemical bonding (G_d), frictional bond (τ_0) and slip-hardening coefficient (β) was obtained from Hui Ma's test. The Chinese PVA

Fig. 7 Flexural stress – load point deflection relation from bending test.

Fig. 8 Flexural properties of ECC under bending test at 60 days.

Fig. 9 Fracture force versus displacement relationships of ECC matrix.

Table 4 Multiple micro-cracking parameters of ECCs.

Mix ID	Matrix parameters			Interface parameters					Calculate results	
	Fracture force (N)	K_m (MPa $\cdot\sqrt{m}$)	E_m (GPa)	G_d (J/m ²)	τ_0 (MPa)	β	f	f'	J_{tip} (J/m ²)	J_b' (J/m ²)
M1-control	980	0.58	19	2.18	1.27	0	0.2	0.33	17.7	23.7
M2-80CR(15%)	733	0.43	14	1.86	1.36	0	0.2	0.33	13.2	27.1
M3-80CR(25%)	606	0.36	14	1.51	0.91	0	0.2	0.33	9.2	27.8

fiber's parameters and micromechanical parameters used to calculate J_b , are summarized in **Table 1** and **Table 4**, respectively (Courtesy of Mr. Hui Ma). The values of snubbing coefficient (f) and in-situ fiber strength reduction factor (f') shown in **Table 4** were adopted from Wang's PhD dissertation and Kanda's previous work, respectively (Kanda and Li 1998; Wang 2005). As shown in **Table 4**, both G_d and τ_0 show decreasing trend with the addition of crumb rubber. The value of β equals to 0, which seems to suggest that no slip-hardening occurred during the Chinese PVA fiber's pull-out process from the particular matrix. This might change for our case as Kuraray fibers were adopted in our study; nevertheless it is adopted for estimation as this is the closest results we can find. A fiber bridging mathematical models based on two-way fiber pull-out consideration developed by Yang *et al.* (2008) was used to calculate the value of J_b . After calculation based on the above micromechanical parameters, the complementary energy J_b has a slight growth as the crumb rubber content in ECC increase. Combining effect of decreasing J_{tip} and increasing J_b with the addition crumb rubber results in enhanced strain-hardening index SHI ($=J_b/J_{tip}$), which is favourable for saturated multiple cracking behavior and ductility.

As shown in **Fig. 8**, the first flexural cracking strength of ECC mixtures decreases with the addition of crumb rubber contributed by the decrease of matrix's fracture toughness making it easier to crack. For example, compared with M1, first flexural cracking strength of M2, M3 decreases 16% and 21%, respectively. In addition to first flexural cracking strength, the flexural strength of ECC mixtures incorporating crumb rubber also shows a downward trend, which indicates a decrease in fiber bridging capacity by incorporating crumb rubber (Li 2012). This may be attributed that large amount of crumb rubber leads to reduced contact area between fibers and matrix which is very similar to the phenomenon observed in latex-modified ECC (Chen *et al* 2014), thus lowering the fiber/matrix interfacial bond.

Table 5 lists the load-deflection response of ECCs, as list, first flexural cracking energy and fracture energy are evaluated by integrating areas under load-deflection curve of ECC corresponding to first flexural cracking and flexural strength. Toughness index is defined as the ratio of fracture energy to first flexural cracking energy, which indicates the normalized plastic energy dissipation capacity. As listed in **Table 5**, incorporating crumb rubber can increase the toughness index. For ECC with incorporating crumb rubber of 80CR, compared with M1, the toughness index increase 8% and 72%. For ECC with incorporating crumb rubber of 40CR, it increases 5% and 25%. The results show that incorporating finer crumb rubber can effectively improve ECC's energy dissipation capacity more.

Figure 10 shows the crack pattern of ECCs under bending test. As observed from **Fig. 10** that incorporating crumb rubber into ECC decrease crack width while

Table 5 Load-deflection response of ECC.

Mix ID	First flexural cracking energy (J)	Fracture energy (J)	Toughness Index
M1	0.11	8.82	83
M2	0.12	10.77	90
M3	0.13	18.59	143
M4	0.09	8.14	87
M5	0.11	11.38	104

Fig. 10 Crack pattern information of ECCs under bending test.

increase crack number, denoting the replacement of silica sand with crumb rubber can help strain-hardening behavior of ECC. The crack width of concrete has a significant impact on its transport properties, thus influence its service life. The reduction in crack width is beneficial to its durability (Gerard *et al* 1997; Hearn N 1999; Lawler *et al* 2002). In addition to the above results, the crack width of ECC specimen incorporated with 80CR crumb rubber is tighter with more cracks, compared to ECC with 40CR crumb rubber. It shows the positive effect of incorporating 80CR crumb rubber on cracking behavior is more pronounced.

3.4 Drying shrinkage of ECC with crumb rubber

The results of drying shrinkage test of ECC mixtures up to 90 days are shown in **Fig. 11**. Each data point represents an average measurement of three specimens. As displayed in **Fig. 11** drying shrinkage of ECCs is much higher than that of normal concrete, which is attributed to the absence of coarse aggregate in ECC matrix. For all ECC specimens, drying shrinkage achieve a steady stage after 21 days. As illustrated in **Fig. 12**, maximum drying shrinkage of all specimens ranges from 1050×10^{-6} to 1660×10^{-6} at the age of 90 days. Meanwhile, ECCs incorporated with crumb rubber exhibit higher drying shrinkage than that of control mixture at all test age. A plausible explanation for this increase is that the modulus of rubber is much lower and much more flexible than silica sand, thus reducing the internal restraint to shrinkage.

In addition, in term of crumb rubber content, drying shrinkage of ECC increases as percentage of crumb

Fig. 11 Drying shrinkage of ECC as a function of time.

rubber replacement increase. In term of rubber size, drying shrinkage of ECC for the 80CR (smaller size) is larger than that of 40CR case under the same crumb rubber content.

In previous study, considering a 2-D slab under restraint at its ends, Li and Henrik defined a restrained shrinkage cracking potential parameter P as stated in equation (1) (2004).

$$P = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp}) \quad (1)$$

Where ε_{sh} is the free shrinkage strain of material, ε_e is its elastic tensile strain capacity, ε_i is its inelastic tensile strain capacity, and ε_{cp} is its tensile creep strain. ε_{sh} is the maximum strain demand due to shrinkage, while $\varepsilon_e + \varepsilon_i + \varepsilon_{cp}$ is the total material strain capacity. If strain demand exceeds strain capacity, fracture failure occurs in the concrete material.

Table 6 lists the typical range of various strains and cracking potential of normal concrete and ECC. Unlike normal concrete, due to the large tensile strain capacity, ECC has a highly negative cracking potential P , allowing shrinkage deformation to be fully accommodated by multiple micro-cracks.

Qian and Li's study shows a simple linear relation for ECC between tensile strain capacity and deflection capacity under bending test (2007). Given a strain hardening material like ECC, a large deflection capacity also suggests a high tensile strain capacity. From section 3.3, it can be seen that incorporating crumb rubber can improve the deflection of ECC, which may suggest high tensile strain capacity for ECC with crumb rubber. Huang's recent study also demonstrated that crumb rubber can increase ECC's tensile strain capacity (2013).

Combining the above conclusions, although compared to ECC without crumb rubber, the drying shrinkage of ECC incorporated with crumb rubber increase from 1050×10^{-6} of M1-control mixture to 1660×10^{-6} of

Fig. 12 Maximum drying shrinkage of ECCs.

M3-80CR, it is still one order of magnitude lower than the tensile strain capacity of ECC, suggesting that ECC with crumb rubber can accommodate the shrinkage deformation without localized fracture failure. The following restrained ring test results can further confirm the above statement.

3.5 Ring test for restrained shrinkage

To reveal the influence of crumb rubber on the cracking behavior of ECC under restrained shrinkage condition, M1, M3, M5 were adopted in the ring test. The restrained shrinkage of the ECC mixtures caused compressive strain to be developed in the steel ring. The development of the strain of steel ring with specimen age is illustrated in **Fig. 13** for mixtures M1, M3, and M5. As seen in **Fig. 13**, incorporation of crumb rubber decreases the steel ring strain, indicating a reduced restrained shrinkage of ECC with crumb rubber. This may be caused by stress relaxation effect of rubber particles in cement matrix (Turatsinze and Garros 2008). In addition, there is a slight decrease after peak point for all ECC mixtures with or without crumb rubber, compared with sharp decline in case of normal concrete.

Fig. 13 Restrained shrinkage of ECC rings.

Table 6 Typical range of various strains and cracking potential of normal concrete and ECC (Li and Henrik 2004).

Properties	ε_{sh} (%)	ε_e (%)	ε_i (%)	ε_{cp} (%)	P
Concrete	0.04-0.1	0.01	0	0.02-0.06	(-0.03) to 0.07
ECC	0.1-0.15	0.015	2-5	0.07	(-4.99) to (-1.94)

Table 7 Restrained drying shrinkage behavior of ECC.

Mix ID	Crack width (μm)	Crack length (mm)	Crack number
M1	27	74	9
M3	13	53	5
M5	19	48	5

Table 8 Potential for cracking classification.

	M1	M3	M5
Average Stress Rate (S, MPa/day)	0.13	0.12	0.09
Potential for Cracking	Moderate-Low	Moderate-Low	Low

The test results of crack width, total crack length and crack number are summarized in **Table 7** and **Fig. 14**. There are no localized fractures for all ECC ring specimens during testing period, only very tight cracks can be observed on the specimen surface. All specimens show average crack width below $30 \mu\text{m}$. In addition, the crack width of ECC incorporating crumb rubber is lower than that of control mixture. Furthermore, lesser total crack length and crack number were observed for ECC mixtures with crumb rubber.

ASTM standard C-1581 specifies the potential for cracking classification according to two parameters: the net time-to-cracking (t_{cr} , in days) and the average stress rate (S, in MPa/day). As no localized fracture appeared on the surface of ECC ring specimens, the net time-to-cracking has no meaning in this test. The calculated results for average stress rate can be seen in **Table 8**. As shown in **Table 8**, the potentials for cracking of ECC are classified as moderate-low or low level. Incorporation of crumb rubber leads to a reduction in the quantitative value of potential for cracking, which means lower sensitivity of ECC to cracking due to shrinkage length change.

In summary, although ECC with crumb rubber has higher free drying shrinkage, the results of ring test for restrained shrinkage clearly demonstrate the reduction in cracking tendency of ECC incorporated with crumb rubber, which suggests potential benefits in improving durability of ECC under restrained drying shrinkage condition.

3.6 Environment footprint

To evaluate alternative materials' environment impact, life cycle assessment (LCA) is usually used as an important comparable tool in recent year (Keoleian *et al* 2005; Qian *et al* 2013). In this study, a simple comparative LCA analysis of ECCs on CO_2 emission is presented. **Figure 15** shows the LCA model of ECC. In this model, it considers all of the raw ingredients' impact on environment during the whole process of their production, delivery and disposal.

Fig. 14 Crack information of ECCs under restrained shrinkage condition.

Fig. 15 LCA model of ECC.

The computations of carbon dioxide (CO_2) emissions of the composites are based on the inventory data of their ingredients in **Table 9**. The inventory data of all ingredients comes from Chinese life cycle database (CLSD). Waste rubber is usually considered as the waste material, recycling waste rubber will avoid the CO_2 emission during its disposal process, so the CO_2 emission from waste rubber is considered to be negative when calculating. However, crumb rubber is grinded from waste rubber; the grinding process will produce CO_2 emission. Combine the facts that fly ash is a by-product of coal burning power plants and its large demands in the civil construction in China, so the CO_2 emission from fly ash is considered to be zero. The calculation results of the amount of CO_2 emission is displayed in **Table 10**.

As listed in **Table 10**, the amount of CO_2 emission shows the decrease trend as the percentage of crumb rubber replacement increase. Compared with ECC without crumb rubber, the CO_2 emission of rubberized ECC with the replacement ratio of 15%, 25% decrease 18% and 30%, respectively. Incorporating crumb rubber into ECC can consume the waste rubber, thus avoid

Table 10 CO_2 emission of ECC (kg/m^3).

Sand replacement (% Vol.) by Crumb rubber	0	15%	25%
CO_2 emission	484	396	338

Table 9 Carbon intensities of ingredients of various concretes.

Ingredients	Cement	PVA fiber	HRWR	Waste rubber, grinding	Silica sand	Waste rubber, disposal	Fly ash
CO_2 emissions $\text{kg-CO}_2/\text{kg}$	0.98	2.7	1.22	0.62	0.045	3.18	0

environment pollution during its disposal process and provide a disposal method of waste rubber. Meanwhile, it also reduces the volume of silica sand used in ECC, thus reduce the quartz mine exploitation and production of silica sand. Therefore using crumb rubber to replace silica sand help ECC to be more environmental friendly.

4. Conclusions

In this paper, the influence of crumb rubber on ECC mechanical and shrinkage properties were studied. Based on the experimental results and discussions, the following specific conclusions can be drawn:

- (1) The density of ECC decreases with the increasing percentage of crumb rubber replacement. The reduction effect of crumb rubber on density is more pronounced when smaller sized crumb rubber is used. The density of ECC with crumb rubber ranges from 1600 kg/m³ to 1710 kg/m³ which can be classified as light weight concrete.
- (2) Incorporating crumb rubber increase the flexural deflection capacity of ECC, with the additional benefit of reduced crack width, which is beneficial to its durability. The effect of crumb rubber on ECC flexural deflection capacity is more pronounced when smaller particle size (80CR) is used. However, crumb rubber adversely affects ECC's strength properties, such as compressive strength and flexural strength, with about 35% reduction of compressive strength.
- (3) Drying shrinkage of ECC increases with the amount of crumb rubber in the mixture. Drying shrinkage of ECC for the 80CR case is larger than that of 40CR case under the same crumb rubber content. However, due to the high deformation capacity, ECC with crumb rubber may still be able to accommodate the shrinkage deformation without localized fracture failure. The results of ring test for restrained shrinkage show that incorporation of crumb rubber lowers sensitivity of ECC to cracking due to shrinkage length change.
- (4) As the percentage of crumb rubber replacement increase, CO₂ emission have the decrease trend denoting crumb rubber replacement of silica sand help ECC reduce its environmental impact.

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